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Bethesda, MD 20084-5000

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BASIC Desk-Top Computer Program for the Three-Dimensional Static Configuration of an Extensible Flexible Cable in a Uniform Stream
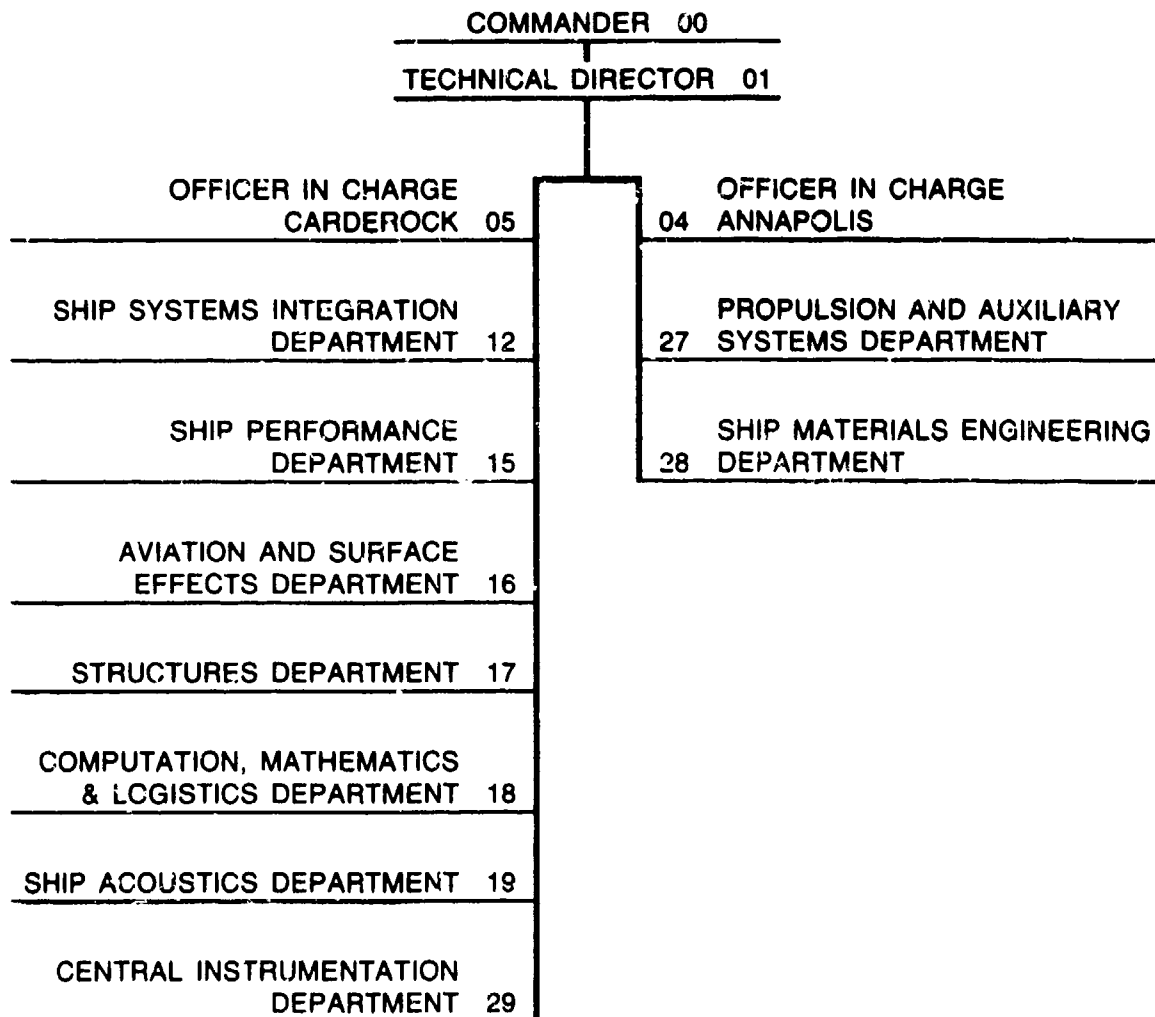
by
Richard K. Knutson

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A generalized computer program for predicting the three-dimensional, static configurations and tensions of extensible, flexible cable systems is described. The program is written in BASIC language for use on desktop computers. The report includes development of the equations, descriptions of the program, instruction for program usage, sample problems, and a program listing for a Hewlett-Packard 9836 desktop computer.

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NOTATION

A_c	Strength member cross-sectional area
A_o	Constant coefficient in hydrodynamic loading function
A_n	Coefficient of $\cos(n\phi)$ terms in hydrodynamic loading function
B	Cable buoyancy in fluid
B_n	Coefficient of $\sin(n\phi)$ terms in hydrodynamic loading function
C_R	Cable normal drag coefficient based on frontal area
C_s	Cable side force coefficient based on frontal area
d	Cable diameter or thickness
E_t	Modulus of elasticity at any point on a stress-strain curve
E_o	Slope of stress-strain curve at zero stress
E_1	Coefficient of stress term in equation for modulus of elasticity
F	Cable hydrodynamic force component per unit length normal to a cable element in the plane defined by the cable element and the free stream direction
F_s	Cable hydrodynamic side force per unit length at the orientation of the cable that produces the maximum value
F_x, F_y, F_z	Body or cable force components in the X-, Y-, and Z-directions
f	Pode frictional parameter
f_n, f_t, f_s	Normal, tangential, and side force hydrodynamic loading functions
G	Cable hydrodynamic force component per unit length tangential to a cable element
H	Cable hydrodynamic force component per unit length normal to the plane defined by a cable element and the free-stream direction

R   Cable drag per unit length when the cable is normal to the free-
           stream direction

R_e Reynolds number

s   Stretched cable length

s_0 Unstretched cable length

Sinc   Cable length printout interval

T   Cable tension

V   Free-stream velocity

W   Cable weight per unit length in a fluid

W_a Cable weight per unit length in air

X   Axis of space-fixed orthogonal coordinate system positive in
           direction of tow (negative in free-stream direction)

Y   Axis of space-fixed orthogonal coordinate system positive to the
           right

Z   Axis of space-fixed orthogonal coordinate system positive in the
           direction of gravity

X_1, Y_1, Z_1 Intermediate coordinate system defined by a rotation of angle β
           about the X-axis

x, y, z   Distances along the X, Y, and Z directions

β Cable kite angle measured from the Z-axis to the tangent of a cable
           element projected onto the Y-Z plane

ϵ Cable strain

ν Fluid kinematic viscosity

ρ Fluid density

σ Cable stress

ϕ Towline angle measured from the free-stream direction (X-axis) to the tangent of a cable element

ABSTRACT

A generalized computer program for predicting
the three-dimensional, static configurations and
tensions of extensible, flexible cable systems is
described. The program is written in BASIC lan-
guage for use on desktop computers. The report
includes development of the equations, description
of the program, instruction for program usage, sam-
ple problems, and a program listing for a Hewlett-
Packard 9836 desktop computer.

ADMINISTRATIVE INFORMATION

INTRODUCTION

This report describes a generalized computer program for predicting the three-dimensional, static configurations and tensions of extensible, flexible cable systems in a uniform stream. The program is written in BASIC language and is specifically intended to provide time-efficient solutions on a desktop computer. Although the program initially was written for use with Hewlett-Packard (HP) computers, it can be adapted with suitable variations in input/output format to other computers that use BASIC. To date, the program has been used on an HP-9826, an HP-9835, an HP-9836, and an HP-87. A program listing for the HP-9836 is contained in the Appendix.

The program is designed to solve initial value problems when the conditions at one end of the cable are known. Boundary value problems must be solved by an

iterative procedure to satisfy prescribed conditions at both ends of the cable. The program allows the cable to assume any configuration without regard to or prior knowledge of cable quadrant. The correct configuration is automatically established by the signs of the initial force components. Cable elasticity is entered as an option. In some cases, as for example with steel cables, elongation may be insignificant. If this is the case, program input is simplified by choosing the nonelastic option. If elongation is significant, as with many composite and synthetic lines, then the elastic option will provide greater accuracy. To use this option, cable elastic modulus and cross-sectional area must be entered as input data. The elastic modulus may be entered either as a constant or as a linear function of cable stress. Synthetic lines frequently exhibit a variable modulus proportional to stress.

The program allows intermediate bodies to be added at any desired point along the cable. In addition, certain properties may be changed along the cable as desired; for example, the cable may be part ribbon-faired and part bare or the fluid may change from water to air. Trail, kite, depth, and cable angle stop values also may be imposed. To include an intermediate body or to change a cable parameter, the cable length to that point or a stopping parameter is specified. The program then will calculate the cable configuration to the specified value and request the option desired. In this way, the computation can be continued to any desired point of termination.

This report includes derivations of the generalized equations which govern the static configuration and tension. Also, the assumed representations of the fluid forces and cable elastic properties are discussed in detail. Finally, the computer program, including the method of solution and its usage, is described.

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DERIVATION OF CABLE CONFIGURATION EQUATIONS

The differential equations describing the three-dimensional static configuration and tension of a cable in a uniform stream are derived from the equilibrium of external forces acting on an element of the cable. A free-body diagram showing a segment of cable of elemental length ds acted upon by hydrodynamic, hydrostatic, gravitational, and tension forces is illustrated in Fig. 1. The (X, Y, Z) coordinate system shown is a right-hand, orthogonal system fixed in space with the X-axis positive in the direction of tow (or negative in the free-stream direction) and the Z-axis positive in the direction of gravity.

The equations are conveniently derived for an orthogonal coordinate system fixed to the cable. In Fig. 1, the hydrodynamic force has been resolved into components Fds, Gds, and Hds where F is the force component per unit length normal to the cable in the plane defined by the cable element and the free-stream direction, G is the force component per unit length tangential to the cable, and H is the (side) force component per unit length normal to the plane defined by the cable element and the free-stream direction. The cable-fixed coordinate system defined by the directions of F, G, and H may be obtained by first rotating the spatial system by an angle β about the X-axis and then rotating the resulting intermediate (X_1, Y_1, Z_1) coordinate system by an angle ϕ about the Y_1-axis. In towed systems nomenclature, the angles β and ϕ generally are referred to as the kite angle and the cable angle, respectively. Since the orientation of the cable changes in space, the angles β and ϕ are functions of cable length s.

For equilibrium, the sums of the force components in each of the directions F, G, and H must all be zero. As shown in Fig. 1, the sum of the force components in the direction of F is

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T + dT/2

+ dβ/2

Φ + dΦ/2

Φ

FREE-STREAM
DIRECTION

Gds

β + dβ/2

+ X

+ s

Bds

Φ

Hds

β

Fds

W_a ds

+ Y

β − dβ/2

+ Z

Φ − dΦ/2

Φ

− dβ/2

T − dT/2
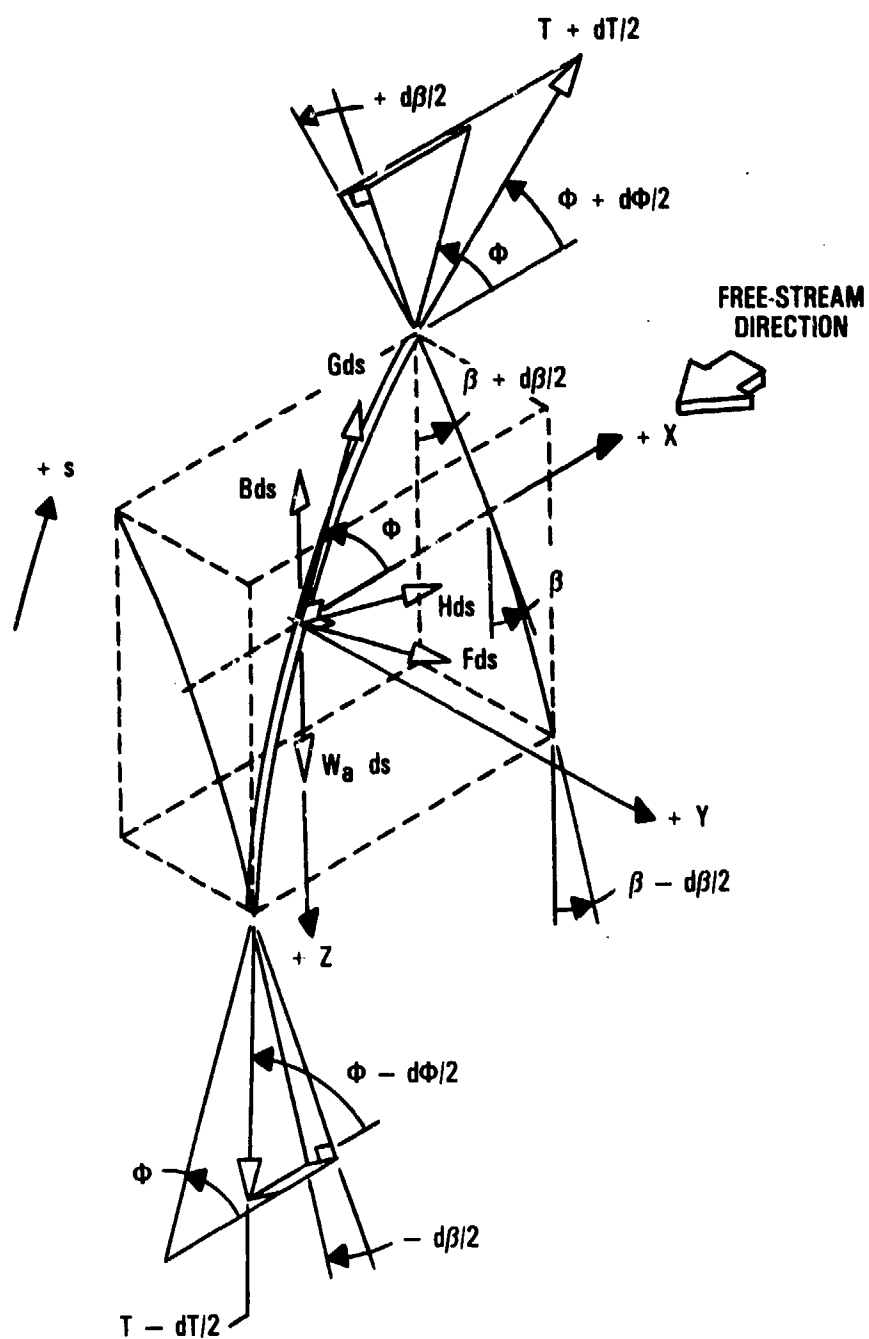
Fig. 1. Forces acting on a segment of cable of elemental length ds.

$$Fds + (W_a - B) \cos\beta \cos\phi \, ds$$

$$-(T + \tfrac{1}{2}dT) \sin(\phi + \tfrac{1}{2}d\phi) \cos(\tfrac{1}{2}d\beta) \cos\phi$$

$$+(T + \tfrac{1}{2}dT) \cos(\phi + \tfrac{1}{2}d\phi) \sin\phi \qquad\qquad (1)$$

$$+(T - \tfrac{1}{2}dT) \sin(\phi - \tfrac{1}{2}d\phi) \cos(-\tfrac{1}{2}d\beta) \cos\phi$$

$$-(T - \tfrac{1}{2}dT) \cos(\phi - \tfrac{1}{2}d\phi) \sin\phi = 0$$

where

F is the hydrodynamic force component per unit length normal to a cable element in the plane defined by the cable element and the free-stream direction,

s is the stretched cable length,

W_a is the cable weight per unit length in air,

B is the cable buoyancy per unit length,

T is the cable tension,

β is the kite angle measured from the Z-axis to the tangent of the cable-element projection onto the Y-Z plane, and

ϕ is the cable angle measured from the free-stream direction (X-axis) to the tangent of the cable element.

From trigonometry,

$$\sin(\phi + \tfrac{1}{2}d\phi) = \sin\phi \cos(\tfrac{1}{2}d\phi) + \cos\phi \sin(\tfrac{1}{2}d\phi) \qquad (2a)$$

$$\cos(\phi + \tfrac{1}{2}d\phi) = \cos\phi \cos(\tfrac{1}{2}d\phi) - \sin\phi \sin(\tfrac{1}{2}d\phi) \qquad (2b)$$

$$\sin(\phi - \tfrac{1}{2}d\phi) = \sin\phi \cos(\tfrac{1}{2}d\phi) - \cos\phi \sin(\tfrac{1}{2}d\phi) \qquad (2c)$$

$$\cos(\phi - \tfrac{1}{2}d\phi) = \cos\phi \cos(\tfrac{1}{2}d\phi) + \sin\phi \sin(\tfrac{1}{2}d\phi). \qquad (2d)$$

Also, since $d\phi$ and $d\beta$ approach zero,

$$\cos(\tfrac{1}{2}d\phi) = 1, \qquad\qquad (3a)$$

$$\sin(\tfrac{1}{2}d\phi) = \tfrac{1}{2}d\phi, \qquad\qquad (3b)$$

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$$\cos(\tfrac{1}{2}d\beta) = 1, \text{ and} \tag{3c}$$

$$\cos(-\tfrac{1}{2}d\beta) = 1. \tag{3d}$$

Substituting Eqs. 2 and 3 into Eq. 1 and then expanding and combining terms gives

$$Fds + (W_a - B) \cos\beta \cos\phi ds - Td\phi = 0$$

or

$$-T \frac{d\phi}{ds} + F + (W_a - B) \cos\beta \cos\phi = 0. \tag{4}$$

The sum of the force components in the direction of G is

$$Gds - (W_a - B) \cos\beta \sin\phi ds$$

$$+(T + \tfrac{1}{2}dT) \sin(\phi + \tfrac{1}{2}d\phi) \cos(\tfrac{1}{2}d\beta) \sin\phi$$

$$+(T + \tfrac{1}{2}dT) \cos(\phi + \tfrac{1}{2}d\phi) \cos\phi \tag{5}$$

$$-(T - \tfrac{1}{2}dT) \sin(\phi - \tfrac{1}{2}d\phi) \cos(-\tfrac{1}{2}d\beta) \sin\phi$$

$$-(T - \tfrac{1}{2}dT) \cos(\phi - \tfrac{1}{2}d\phi) \cos\phi = 0$$

where G is the hydrodynamic force component per unit length tangential to the cable element.

Substituting Eqs. 2 and 3 into Eq. 5 and then expanding and combining terms gives

$$Gds - (W_a - B) \cos\beta \sin\phi ds + dT = 0$$

or

$$\frac{dT}{ds} + G - (W_a - B) \cos\beta \sin\phi = 0. \tag{6}$$

The sum of the force components in the direction of H is

$$Hds - (W_a - B) \sin\beta ds$$

$$-(T + \tfrac{1}{2}dT) \sin(\phi + \tfrac{1}{2}d\phi) \sin(\tfrac{1}{2}d\beta) \tag{7}$$

$$+(T - \tfrac{1}{2}dT) \sin(\phi - \tfrac{1}{2}d\phi) \sin(-\tfrac{1}{2}d\beta) = 0$$

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where H is the hydrodynamic force component per unit length normal to the plane defined by the cable element and the free-stream direction.

Since $d\beta$ approaches zero,

$$\sin(\tfrac{1}{2}d\beta) = \tfrac{1}{2}d\beta \text{ and} \tag{8a}$$

$$\sin(-\tfrac{1}{2}d\beta) = -\tfrac{1}{2}d\beta. \tag{8b}$$

Substituting Eqs. 2, 3 and 8 into Eq. 7 then expanding and combining terms gives

$$Hds - (W_a - B) \sin\beta ds - T\sin\phi d\beta - \tfrac{1}{2}dTd\beta d\phi\cos\phi = 0$$

or, since the third order term is negligible,

$$-T\sin\phi \frac{d\beta}{ds} + H - (W_a - B) \sin\beta = 0. \tag{9}$$

Equations 4, 6, and 9 are the three differential equations of force equilibrium in the cable-fixed reference system. The differential equations for cable displacements in the X, Y, and Z directions can be obtained from Fig. 1 by inspection. They are

$$dx = ds \cos\phi \qquad \text{or} \qquad \frac{dx}{ds} = \cos\phi, \tag{10}$$

$$dy = -ds \sin\phi \sin\beta \qquad \text{or} \qquad \frac{dy}{ds} = -\sin\phi \sin\beta, \text{ and} \tag{11}$$

$$dz = -ds \sin\phi \cos\beta \qquad \text{or} \qquad \frac{dz}{ds} = -\sin\phi \cos\beta \tag{12}$$

where x, y, and z are distances along the X, Y, and Z directions, respectively.

FLUID HYDRODYNAMIC FORCE COMPONENTS

The fluid hydrodynamic force components Fds, Gds, and Hds arise, in the cases of F and G, from fluid drag forces and, in the case of H, from fluid side or lift forces.

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FLUID DRAG FORCES

The fluid drag force components per unit cable length F and G lie in the plane defined by a cable element and the free-stream flow direction. Generally these components are assumed to be the product of a drag per unit length that is a function only of Reynolds number and a loading function that is a function only of cable angle ϕ. Under this convention, the normal force per unit length F and the tangential force per unit length G are of the following form:

$$F(Re,\phi) = -R(Re) \cdot f_n(\phi) \tag{13}$$

$$G(Re,\phi) = -R(Re) \cdot f_t(\phi) \tag{14}$$

where

R   is the cable drag per unit length when the cable is normal to the free-stream direction ($R = \frac{1}{2}\rho C_R V^2 d$),

Re   is the Reynolds number ($Re = Vd/\nu$),

ρ is the fluid density,

C_R is the cable normal drag coefficient based on frontal area expressed as a function of Reynolds number,

d   is the stretched cable diameter,

V   is the free-stream flow velocity,

ν is the fluid kinematic viscosity, and

f_n, f_t are the normal and tangential hydrodynamic loading functions, respectively.

The negative (-) signs in Eqs. 13 and 14 appear since the cable drag is in the negative (-) X direction as defined in Fig. 1.

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The hydrodynamic loading functions $f_{n,t}$ are commonly expressed in the form of a trigonometric series[1,2] as follows:

$$f_{n,t}(\phi) = A_o + \sum_{n=1}^{\infty} A_n \cos(n\phi) + B_n \sin(n\phi) \tag{15}$$

where A_o, A_n, and B_n are constant coefficients. Generally, cable loading is adequately expressed by inclusion of only the first five terms ($n = 2$) of Eq. 15.

FLUID SIDE FORCES

Fluid side forces occur as a result of cable instabilities or lateral shape asymmetries. In the case of twisted wire ropes or double-armored electro-mechanical cables, the helical twist of the exposed wire strands causes a lateral shape asymmetry which can produce significant side forces.

In a manner similar to that used with drag forces, the side force component per unit length H is expressed conveniently as the product of a side force that is a function only of Reynolds number and a loading function that is a function only of cable angle ϕ as follows:

$$H(Re, \phi) = F_s(Re) \cdot f_s(\phi) \tag{16}$$

where

F_s is the cable side force per unit length at the orientation of the cable that produces the maximum value ($F_s = \frac{1}{2}\rho C_s V^2 d$),

C_s is the cable side force coefficient based on frontal area expressed as a function of Reynolds number, and

f_s is the hydrodynamic side force loading function.

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The maximum side force F_s may or may not occur when the cable is normal to the free-stream. The side force loading function f_s also is adequately expressed using the first five terms of the trigonometric series indicated in Eq. 15.

CABLE ELONGATION

The cables used in towing and mooring applications generally exhibit three types of elongation as follows:

1. Permanent Elongation -- This type is nonrecoverable and is associated primarily with fabrication looseness inherent in new cables, ropes, and lines before the wires or strands are seated. The amount of permanent elongation depends on the construction type and the degree of pre-stressing. Permanent elongation becomes fairly constant after re/eated loadings. For wire rope, this type of elongation is typically between 0.25 and 0.33 percent of initial length depending upon maxi,;m stress.[3]

2. Creep Elongation -- Th*s type of elongation is associated with material properties and depends on both the tensile stress and the length of time the stress is applied. Creep elongation is recoverable over a period of time after the stress is reduced or removed. Metallic cables and certain forms of composite lines exhibit minimal creep within normal working stresses, whereas many synthetic lines exhibit noticeable creep.

3. Elastic Elongation -- This type of elongation is immediately recoverable and depends on the type of construction as well as the material proper-ties. Elastic elongation is essentially proportional to stress in most metallic cables and ropes but is frequently a nonlinear function of

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stress in synthetic lines - most notably nylon, polyester, and polypropylene.

Of the three types of elongation, only elastic elongation is examined in this report and included in the computer program. Permanent elongation can be accounted for by assuming a preconditioned cable. Creep elongation is difficult to treat because a stress-time history is required.

Elastic elongation curves for representative towline types are shown in Fig. 2. These curves are based on vendor data and are intended to illustrate general relationships rather than to provide specific design information. Ideally the elastic properties of each towcable should be verified individually. From standard mechanics of deformable media[4], stress is related to elastic strain by the equation

$$E_t = \frac{d\sigma}{d\epsilon} \tag{17}$$

where

E_t is the slope of the stress-strain curve at any point and generally is referred to as the modulus of elasticity,

σ is the cable stress ($\sigma \equiv T/A_c$),

T is the cable tension,

A_c is the cable or strength-member cross-sectional area,

ϵ is the cable strain ($\epsilon \equiv \frac{s-s_o}{s_o}$),

s is the stretched cable length, and

s_o is the unstretched cable length.

The cable modulus of elasticity in Eq. 17 depends on cable construction and, therefore, should not be confused with material modulus of elasticity which generally is higher. For the nonlinear stress-strain curves of Fig. 2, the

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modulus of elasticity E_t can be approximated by a linear function of stress σ as follows:

$$E_t = E_0 + E_1 \sigma \tag{18}$$

where

E_0 is the slope of the stress-strain curve at a stress σ equal to zero, and

E_1 is a proportionality factor.

Substituting Eq. 18 into Eq. 17 and solving for strain, the result is,

$$d\varepsilon \equiv d\left(\frac{s - s_0}{s_0}\right) = \frac{d\sigma}{(E_0 + E_1 \sigma)} = \frac{1}{A_c}\left[\frac{dT}{(E_0 + E_1 T/A_c)}\right]. \tag{19}$$

Equation 19 can be integrated between zero and any value of T to obtain the strain or stretch at that value. The result is[5]

$$\frac{s - s_0}{s_0} = \frac{K}{A_c} \qquad \text{or} \qquad s = s_0\left(1 + \frac{K}{A_c}\right) \tag{20a}$$

where

$$K = \frac{A_c}{E_1} \log_e\left[\frac{(E_0 + E_1 T/A_c)}{E_0}\right], \quad E_1 \neq 0 \tag{20b}$$

or

$$K = \frac{T}{E_0}, \quad E_1 = 0 \tag{20c}$$

Equation 20a,c is the classical linear stress-strain relationship. For the nonlinear stress-strain curves shown in Fig. 2, Eq. 20a,b predicted the stretched cable length to within ±0.5 percent at all stress levels.

In terms of an incremental cable segment of unstretched length ds_0, Eq. 20a becomes

$$ds = ds_0\left(1 + \frac{K}{A_c}\right) \tag{21}$$

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1. 6X7 PLOW STEEL
2. PARALLEL STRAND KEVLAR 29
3. PARALLEL STRAND POLYESTER
4. BRAIDED POLYESTER
5. PARALLEL STRAND NYLON
6. BRAIDED NYLON
7. THREE-STRAND POLYPROPYLENE

—————— VENDOR DATA
- - - - - - APPROXIMATION USING EQUATION 20
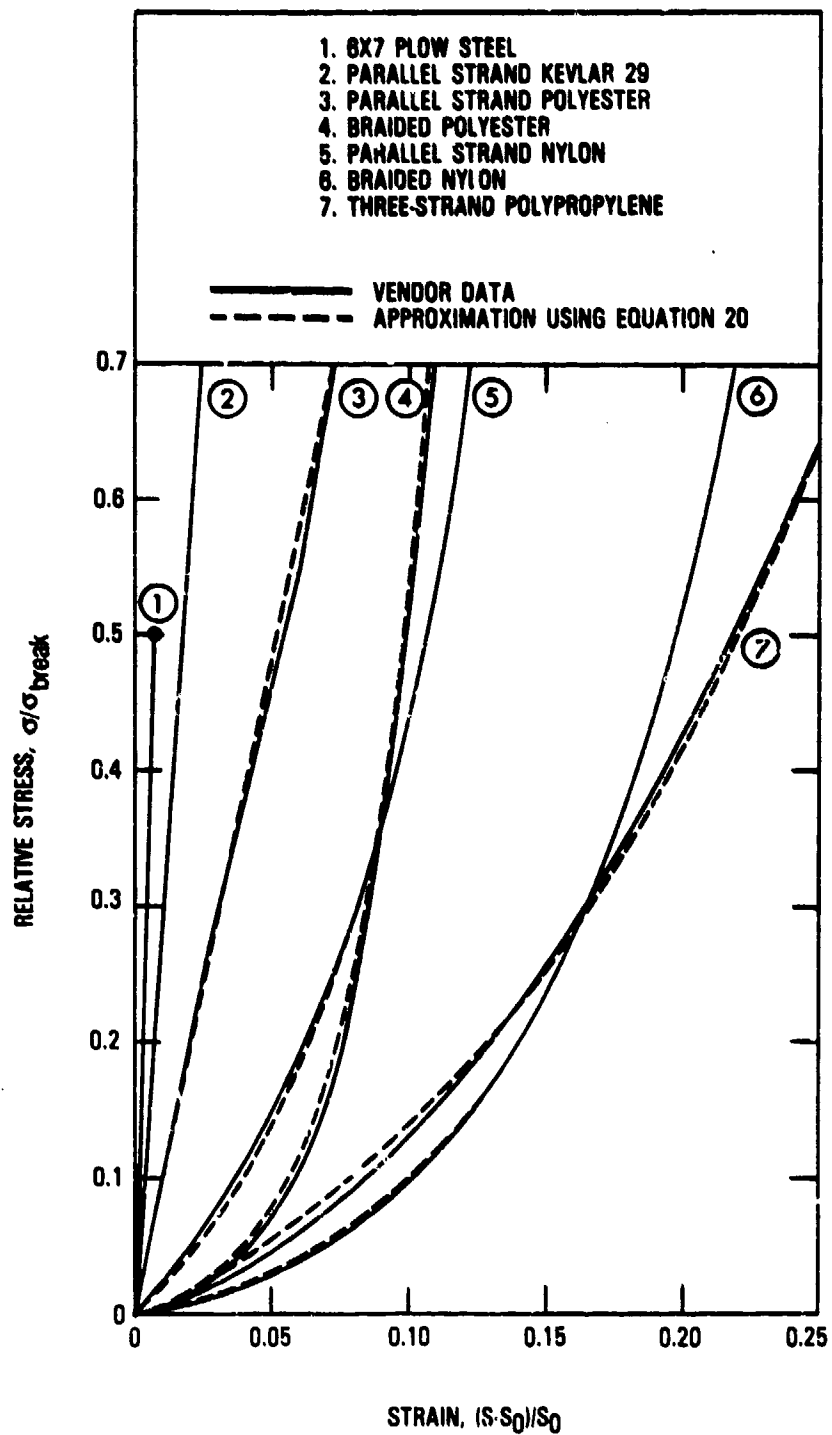
Fig. 2. Elastic elongation of various towline types.

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As the cable stretches under tension, both its diameter and its stretched weight per unit length decreases. For a homogeneous and isotropic material, transverse strain is related to axial strain by Poisson's ratio.[4] However, most cables are neither homogeneous nor isotropic, and therefore the assumption is made here that the stretched cable preserves its original volume. Under this assumption, the stretched diameter d and stretched weight in the fluid per unit length W are related to their unstretched states d_c and W_o, respectively, by the following relationships:

$$d = d_o \left[\frac{1}{(1 + K/A_c)} \right]^{1/2}$$

(22)

and,

$$W = W_o \left[\frac{1}{(1 + K/A_c)} \right]$$

(23)

where K is defined in Eq. 20b,c.

Substitution of Eqs. 21, 22, and 23 into the configuration equations allows solutions of elastically elongated cables to be obtained in terms of unstretched reference parameters.

PROGRAM DESCRIPTION

The computer program consists of a main input section and six subroutines.

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MAIN INPUT SECTION

The input section provides a format for entering fluid density, towing speed (or flow speed), initial body force components in the three principal directions X, Y, and Z, cable characteristics, cable length printout interval, and various spatial conditions at which the integration is to stop. The initial cable angle φ and kite angle β are automatically determined within the program by the magnitudes and directions of the body force components. This method of entering body force allows the integration to proceed without regard to or prior knowledge of the cable angle quadrant. The program also will compute cable configurations, with a small starting error, when the initial input force is zero. This feature is useful in towed array problems where usually no body is attached to the outboard end of the array.

SUBROUTINE TANGLE

Subroutine "Tangle" computes initial tension T, cable angle φ, and kite angle β using the input force components. Starting values for these variables are required to initiate the program solution.

SUBROUTINE CRITANG

Subroutine "Critang" computes the cable angle φ and kite angle β when the starting input force is zero. Although this subroutine is not required for the program to obtain a solution, it does improve the accuracy at the outboard end of the cable and does reduce computation time considerably when the starting force is zero.

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SUBROUTINE INTEGRATOR

Subroutine "Integrator" solves the differential equations of force equilibrium, Eqs. 4, 6, and 9, using a self-starting, modified Euler's method. A large integration step Δs is used in the program to minimize solution time. Initially the step size is set equal to the specified printout interval Sinc or to a length increment of 50 ft, whichever is less. At each integration interval, the calculation is iterated about the changes in cable angle $\Delta\phi$ and kite angle $\Delta\beta$ until succeeding iteration values of $\Delta\phi$ and $\Delta\beta$ are within ± 0.0002 rad (± 0.01 deg). If, however, the computation produces angle changes greater than 0.09 rad (5 deg) or the computation does not converge within 10 iteration loops, then the step size is reduced, and the iteration is repeated for the smaller value. By this technique, the integration step size is efficiently adjusted to provide a good degree of accuracy and a short computation time. Once the variables T, ϕ, and β are determined, the cable displacement variables x, y, and z (Eqs. 10, 11, and 12) are computed using the average calculated values of ϕ and β between successive integration steps. A flow chart of the integration process is shown in Fig. 3.

In general, the trigonometric series used to specify the cable hydrodynamic loading functions is composed of both sin and cos terms and provides the correct loading value only in the cable angle range ϕ from zero to 90 deg. Therefore, if a computation falls outside this range, a corrected value must be used. This correction is made within the program by assuming that the normal loading function for all types of cables and the side loading function for faired cables are symmetrical about $\phi = \pm 90$ deg and complementary about $\phi = 0$ deg, that the tangential loading function for all types of cables is symmetrical about $\phi = 0$ deg and complementary about $\phi = \pm 90$ deg, and that the side loading function for

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SELECT STEP SIZE

$\triangle S = S_{po} + S_{inc} - S_1$
IF $\triangle S > 50$ THEN $\triangle S = 50$
($S_{po} = S_1$ at printout)

UPDATE

$T_0 = T_1$
$\beta_0 = \beta_1$
$\Phi_0 = \Phi_1$
$S_0 = S_1$

ADJUST STEP SIZE

$\triangle S = \triangle S/2$

INITIALIZE VARIABLES

$I = 0$
$\triangle T^{(0)} = 0$
$\triangle \beta^{(0)} = 0$
$\triangle \Phi^{(0)} = 0$

ADJUST STEP SIZE

$\triangle S = \triangle S \cdot 0.07/\triangle \beta^{(I)}$
OR
$\triangle S = \triangle S \cdot 0.07/\triangle \Phi^{(I)}$

$I = 10$

$I < 10$

COMPUTE AVG VALUES

$I = I + 1$
$\bar{T}^{(I)} = T_0 + \triangle T/2^{(I-1)}$
$\bar{\beta}^{(I)} = \beta_0 + \triangle \beta/2^{(I-1)}$
$\bar{\Phi}^{(I)} = \Phi_0 + \triangle \Phi/2^{(I-1)}$
$F(\bar{\Phi}), G(\bar{\Phi}), H(\bar{\Phi})$

COMPUTE VARIABLES

$\triangle T^{(I)}, \triangle \beta^{(I)}, \triangle \Phi^{(I)}$

CHECK VARIATION

$\triangle \beta^{(I)} < 0.09$ rad?
AND
$\triangle \Phi^{(I)} < 0.09$ rad?

NO

YES

CHECK CONVERGENCE

$|\triangle \beta^{(I)} - \triangle \beta^{(I-1)}| < 0.0002$ rad?
$|\triangle \Phi^{(I)} - \triangle \Phi^{(I-1)}| < 0.0002$ rad?

NO

YES

COMPUTE VALUES

$T_1 = T_0 + \triangle T^{(I)}$
$\beta_1 = \beta_0 + \triangle \beta^{(I)}$
$\Phi_1 = \Phi_0 + \triangle \Phi^{(I)}$
$S_1 = S_0 + \triangle S^{(I)}$
x_1, y_1, z_1

Fig. 3. Flow chart of integration technique.

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stranded (twisted) cables is complementary about both ϕ = 0 deg and ϕ = ±
90 deg. These relationships are summarized in Table 1.

The integration is terminated at the maximum specified value of cable length
Smax or at a specified stop value corresponding to trail distance x, kite dis-
tance y, depth z, or cable angle ϕ. After each integration step, the program com-
pares the computed value to the specified stop value. If a specified stop value
has been exceeded, the program performs a simple iteration to converge on the
specified value. The iteration works by halving the cable length segment which
brackets the point until the desired stop value is approached to within a certain
limiting criterion. The convergence criterion is 0.01 ft for distance variables
and 0.0005 rad (0.03 deg) for the angular variable.

Table 1 - Relationships of the hydrodynamic loading functions
in various quadrants of cable angle ϕ.

Loading Function	Cable Angle Range (deg)			
	ϕ	−180 TO −90	−90 TO 0	0 TO +90	+90 TO +180
	ϕ_1 =	180 minus $|\phi|$	$|\phi|$	ϕ	180 minus ϕ
Normal	$f_n (\phi)$ =	$-f_n (\phi_1)$	$-f_n (\phi_1)$	$+f_n (\phi_1)$	$+f_n (\phi_1)$
Tangential	$f_t (\phi)$ =	$-f_t (\phi_1)$	$+f_t (\phi_1)$	$+f_t (\phi_1)$	$-f_t (\phi_1)$
Side (stranded)	$f_s (\phi)$ =	$+f_s (\phi_1)$	$-f_s (\phi_1)$	$+f_s (\phi_1)$	$-f_s (\phi_1)$
Side (faired)	$f_s (\phi)$ =	$-f_s (\phi_1)$	$-f_s (\phi_1)$	$+f_s (\phi_1)$	$+f_s (\phi_1)$

SUBROUTINES PODE, RIBBON, AND OTHER LOADING

Subroutines "Pode" and "Ribbon" provide hydrodynamic loading functions for
bare and ribbon-faired cables, respectively. These subroutines are included for
convenience since these types of cables are used frequently. Subroutine "Other

loading" allows the user to specify the coefficients of the trigonometric series corresponding to any desired loading. Pode and ribbon-faired loading are discussed in the next paragraphs.

Pode Normal and Tangential Hydrodynamic Loading

Pode hydrodynamic loading[7] is commonly used to predict the performance of unfaired (bare) cable systems. In terms of the previously discussed trigonometric series (refer to section on FLUID DRAG FORCES), the normal and tangential loading functions f_n and f_t are, respectively,

$$f_n = \sin^2\phi = 0.5 - 0.5 \cos(2\phi)$$

$$f_t = f \tag{25}$$

where

f is the Pode frictional parameter.

Ribbon Normal and Tangential Hydrodynamic Loading

Normal and tangential hydrodynamic loading functions have been obtained from at-sea data for a 0.78-in. (19.8-mm) diameter double-armored electro-mechanical cable.[8] The ribbon used was 0.015-in. (0.381-mm)-thick, 0.78-in. (19.8-mm)-wide polyurethane. Ribbon spacing was 0.78 in. (19.8 mm) between centers. The ribbon length (equal to one-half the loop length) was six times the cable diameter or 4.68 in. (237.7 mm). The normal and tangential loading functions f_n and f_t obtained for this ribbon faired cable are, respectively,

$$f_n = 0.4986 - 0.2499 \cos\phi + 0.2527 \sin\phi - 0.2487 \cos(2\phi) \tag{26}$$

$$f_t = -0.2255 + 0.3417 \cos\phi + 0.2255 \sin\phi - 0.0811 \sin(2\phi). \tag{27}$$

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These loading functions correspond to a normal drag coefficient,

$$C_R = 5.7467 - 0.93 \log_{10} Re; \quad 50,000 < Re < 120,000 \tag{28}$$

where Re is Reynolds number based on diameter. Hydrodynamic loading may vary with different ribbon geometries, and therefore the above equations should be used with caution.

Bare and Ribbon-Faired Side Force Hydrodynamic Loading

The side force on 1 x 19 and 6 x 19 twisted wire ropes has been measured in a wind tunnel.[9,10] The data, reduced to side loading function form, are shown in Fig. 4. These data represent average values over a Reynolds number range from 32,600 to 43,400 for the 1 x 19 rope and from 16,400 to 83,700 for the 6 x 19 rope.
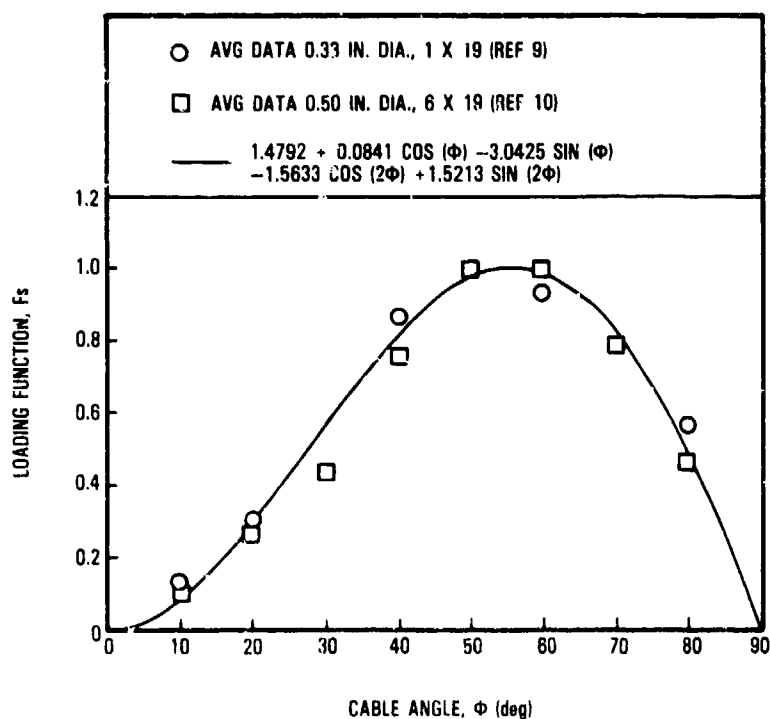
Fig. 4. Hydrodynamic side loading function for two twisted wire ropes.

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The side force coefficients C_s, averaged over the same Reynolds number ranges, are 0.135 and 0.232 for the 1 x 19 and the 6 x 19 ropes, respectively. Average values are given here since the data were scattered to the extent that a reasonable Reynolds number dependency could not be established. A least-squares fit to the side loading data resulted in the following trigonometric series for the side force loading function f_s:

$$f_s = 1.4792 + 0.0841 \cos\phi - 3.0425 \sin\phi - 1.5633 \cos (2\phi)$$

$$+ 1.5213 \sin (2\phi). \tag{29}$$

Although this loading function was determined on the basis of only two cable constructions, the general form probably is consistent with other stranded cables as well, and therefore it has been entered into the program as a general loading function for both bare and ribbon-faired cables. The side force coefficient C_s, however, is strongly influenced by the number of wire strands exposed to the flow, by the twist or helical angle, and possibly by the ribbon geometry.

STORAGE AND TIME REQUIREMENTS

The fully working program without comment statements requires approximately 10,000 bytes of storage on an HP-9836; with comment statements, approximately 13,000 bytes of storage are required. The length of time required to compute a cable configuration depends primarily on the change in cable angle and the tension. On an average, an HP-9836 requires approximately 5 to 10 sec. However, for cases in which the initial input tension is near zero, computing time may increase to 20 sec or more. Computation time also may be greater on other computers. For example, an HP-9835 is approximately three times slower than an HP-9836; an HP-87 is approximately ten times slower.

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ACCURACY

The large integration step size and relatively loose convergence criteria used in the program do not appear to significantly affect accuracy. Comparisons made with other cable programs[11,12] indicate differences of less then 0.05 percent in the output variables for the same input conditions.

PROGRAM USAGE

Data are entered into the program by a series of command statements which appear on the CRT screen. The command statements are listed in Table 2. The program prints the data variables immediately after they are entered to maintain a running check of the values.

COMMENTS CONCERNING DATA INPUT

The following comments refer to command statements listed in Table 2.

1. Command statement number 1 selects the printout medium.

2. The title statement number 2 is dimensioned to allow a title length of up to 80 characters.

3. Statement numbers 5 through 9 request the type of hydrodynamic loading desired. If "Pode" loading is chosen, the statement PODE LOADING will be printed and statement number 6, requesting the Pode frictional parameter, will appear next on the CRT. After the frictional parameter is entered, the program will skip to command statement number 10. Similarly if "Ribbon" loading is chosen, the statement RIBBON LOADING will be printed. If neither "Pode" nor "Ribbon" loading is entered, the coefficients of a generalized loading function will be requested (command statements 7, 8, and 9). Five values for each loading function f_n,

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Table 2. Program command statements.

01	FOR HARDCOPY, ENTER: 1 [For CRT, press CONT]
02	ENTER: TITLE
03	ENTER SPEED: V (Knots)
04	ENTER FLUID MASS DENSITY: Rho (Lb*Sec^2/Ft^4)
05	ENTER CABLE LOADING: Pode=1; Ribbon=2; Other=3
06	ENTER PODE FRICTIONAL PARAMETER: f
07	ENTER NORMAL LOADING FUNC, fs: A0,A1,B1,A2,B2
08	ENTER TANGENTIAL LOADING FUNC, ft: A0,A1,B1,A2,B2
09	ENTER SIDE LOADING FUNC, fs: A0,A1,B1,A2,B2
10	ENTER CABLE NORMAL DRAG COEFF: Cr
11	ENTER CABLE SIDE FORCE COEFF: Cs
12	ENTER CABLE THICKNESS: d (In.)
13	ENTER CABLE WEIGHT IN FLUID: W (Lb/Ft)
14	ENTER CABLE ELASTICITY: Non-Elastic=1; Elastic=2
15	ENTER MODULUS OF ELAS: E=E0+E1*T/Ac (Lb/In.^2)
16	ENTER CABLE CROSS-SECTIONAL AREA: Ac (In.^2)
17	ENTER BODY FORCE COMPONENTS: Fx,Fy,Fz (Lb)
18	ENTER MAXIMUM CABLE LENGTH: Smax (Ft)
19	ENTER CABLE LENGTH PRINTOUT INTERVAL: Sinc (Ft)
20	ENTER LIMIT: Xstop (Ft) [If none, press CONT]
21	ENTER LIMIT: Ystop (Ft) [If none, press CONT]
22	ENTER LIMIT: Zstop (Ft) [If none, press CONT]
23	ENTER LIMIT: Phistop (Deg) [If none, press CONT]
24	ADD BODY, ENTER: 1; ADD CABLE, ENTER: 2 [NEW CASE, press CONT]

f_t, and f_s are required. In each case, the values to be entered represent the coefficients of the following trigonometric series:

$$f_{n,t,s} = A_0 + A_1 \cos\phi + B_1 \sin\phi + A_2 \cos(2\phi) + B_2 \sin(2\phi).$$

After the coefficients of all three loading functions have been entered, the functions with their assigned coefficient values will be printed in the output.

4. Command statement number 14 provides the option of selecting either a nonelastic cable or an elastic cable. If the nonelastic option is chosen, the program skips the command statements (numbers 15 and 16) whicn relate to the elastic properties of the cable. If the elastic option is chosen, the ensuing command statements (numbers 15 and 16) require input of cable (not material) modulus of elasticity and strength-member cr 3s-sectional area. Two values representing the coefficients of the equation

$$E = E_0 + E_1 (T/A_c),$$

where λ_c is cable stress, must be input for the modulus of elasticity. For a linear stress-strain curve, the first coefficient E_0 is the slope of the curve and the second coefficient E_1 is set equal to zero. For a nonlinear stress-strain curve, the coefficient E_0 represents the slope of the stress-strain curve at zero stress and the coefficient E_1 represents a factor proportional to stress. The sign of E_1 must be positive. This method of representing modulus of elasticity is useful for synthetic lines which frequently exhibit nonlinear stress-strain relationships. Modulus of elasticity is discussed further in the section entitled CABLE ELONGATION.

5. Body force is entered into the program (command statement number 17) in the form of components in the three principal directions X, Y, and Z where F_x is positive in the direction of tow (negative in the free-stream direction), F_y is positive to starboard, and F_z is positive in the direction of gravity. Entering body forces in this manner avoids confusion with respect to cable angle values and quadrants. Body drag F_x should be entered as a negative (-) number; a positive (+) value indicates thrust. The initial input force can be either at the fixed end of the cable (which implies a positive value for F_x) or at the towed body or free end of the cable. Care should be exercised, however, in starting a computation at a fixed end; in this case, if the starting cable angle is near the critical angle, the resulting cable shape is exceptionally sensitive to the force component values.

6. If external body force components are input into the program as the initial condition, specified cable length Smax (command statement number 18) should always be positive (+). If a negative cable length is specified, the initial input forces represent internal cable forces rather than external forces. The cable length printout interval Sinc (command statement number 19) can be specified as either positive or negative; the proper sign is selected by the program.

7. Four stopping conditions other than Smax are included in the program (command statement numbers 20 through 23). The conditions Xstop, Ystop, and Zstop will terminate the calculation whenever trail (X-direction), kite (Y-direction), or depth (Z-direction) reach the specified value as measured from the starting point at the initial body. The condition Phistop will terminate the computation when the specified cable angle ϕ

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value is reached. If no stopping condition is specified, the calculations will continue until Smax is reached.

8. Once the computation is completed to the specified stopping point, command statement number 24 will appear on the CRT screen. If the option ADD BODY is chosen, command statement numbers 17 through 23 will reappear on the CRT in sequence. If the option ADD CABLE is selected, command statement numbers 4 through 16 and 18 through 23 will appear on the CRT. The ADD CABLE option allows the cable properties as well as the fluid density (as, for example, from water-to-air) to change. If the option NEW CASE is chosen, the program will print the final cable force components and return to command statement number 1 to begin a new cable configuration.

9. When an HP-9836, an HP-9835, or an HP-9826 is used, most of the input values will be retained unless they are specifically changed or the computer program is stopped. The exceptions are the stopping parameters (command statement numbers 20 through 23). These values must be re-entered each time the command statement appears on the CRT. With an HP-87, however, all values must be re-entered each time a command statement appears on the CRT.

SAMPLE PROBLEMS

The following three sample problems illustrate program usage:

Problem 1 - Submarine Towing a Submerged Buoy

Determine the length of double-armored steel cable necessary to tow a subsurface buoy 300 ft above the deck of a submarine at 10 kn. Ribbon fairing is

attached to the cable for the first 300 ft of length starting at the buoy to reduce cable strumming. Printout of cable variables is desired at 50-ft intervals along the cable length. The cable will be assumed to be nonelastic. The characteristics of the fluid, cable, and buoy are listed in Table 3; program output is listed in Table 4.

Problem 2 - Ship Towing a Paravane

Determine the length of faired towline necessary to tow a paravane 500 ft to the side of a ship at 25 kn. The towline strength member is parallel-strand fiberglass in a epoxy matrix. The ship towpoint is 15 ft above the water surface. Printout of cable variables is desired at 50-ft intervals along the cable length. The characteristics of the fluid, towline, and paravane are listed in Table 5; final program output is listed in Table 6. Note that, since the towline passes through the air-water interface but the total side distance to the ship is specified, the problem is boundary valued and must be iterated to find the side distance at which the towline pierces the water surface.

Problem 3 - Helicopter Towing Two Depressors

A helicopter is required to tow two depressors spaced 50-ft apart along a braided nylon towline at a speed of 20 kn. Determine the length of towline necessary to place the lower depressor at a depth of 75 ft if the helicopter is flying at an altitude of 100 ft. The towline is unfaired. Both depressors produce identical towing forces. Printout of cable variables is desired only at end points of cable segments. The characteristics of the fluids, towline, and depressors are listed in Table 7, program output is listed in Table 8.

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Table 3. Physical characteristics of sample problem 1.

Speed, V (kn)	10.0
Fluid Density, ρ (lb-sec^2/ft^4)	1.9905
Cable	
Diameter, d (in.)	0.35
Weight in Fluid, W (lb/ft)	0.15
Ribbon Loading	
Normal Drag Coefficient, C_r	1.25
Side Force Coefficient, C_s	0.10
Cable Length, Smax (ft)	300.0
Bare (Pode) Loading	
Pode Frictional Parameter, f	0.01
Normal Drag Coefficient, C_r	1.90
Side Force Coefficient, C_s	0.10
Total Depth, Zstop (ft)	300.0
Buoy	
Drag Force, F_x (lb)	-500.0
Side Force, F_y (lb)	0.0
Down Force, F_z (lb)	-2000.0

Table 4. Program output for sample problem 1.

```
----------------------------------------------------------------------
SUBMARINE TOWING A SUBMERGED BUOY USING A STEEL CIRCULAR CABLE
----------------------------------------------------------------------
```

V=10.00 Knots

Rho=1.9905 Lb*Sec^2/Ft^4

RIBBON LOADING

fn= 0.4986-0.2499 COS(Phi)+0.2527 SIN(Phi)-0.2487 COS(2*Phi)+0.0000 SIN(2*Phi)
ft=-0.2255+0.3417 COS(Phi)+0.2255 SIN(Phi)+0.0000 COS(2*Phi)-0.0811 SIN(2*Phi)
fs= 1.4792+0.0841 COS(Phi)-3.0425 SIN(Phi)-1.5633 COS(2*Phi)+1.5213 SIN(2*Phi)

```
        Cr= 1.250
        Cs=  .100
        d=   .350 In.
        W=   .150 Lb/Ft
```

BODY FORCE COMPONENTS
```
        Fx=  -500.00 Lb
        Fy=     0.00 Lb
        Fz= -2000.00 Lb
```

Sref(Ft)	Sstr(Ft)	X(Ft)	Y(Ft)	Z(Ft)	Phi(Deg)	Beta(Deg)	T(Lbs)
0.0	0.0	0.0	0.0	0.0	76.0	180.0	2061.6
50.0	50.0	17.2	.4	46.8	63.9	181.0	2081.1
100.0	100.0	43.1	1.6	89.5	53.9	182.3	2112.2
150.0	150.0	75.4	3.6	127.6	45.8	183.7	2151.6
200.0	200.0	112.2	6.2	161.3	39.4	185.2	2197.1
250.0	250.0	152.3	9.3	191.0	34.2	186.5	2247.2
300.0	300.0	194.7	12.6	217.4	30.0	187.8	2300.5

Rho=1.9905 Lb*Sec^2/Ft^4

PODE LOADING

fn= 0.5000+0.0000 COS(Phi)+0.0000 SIN(Phi)-0.5000 COS(2*Phi)+0.0000 SIN(2*Phi)
ft= 0.0100+0.0000 COS(Phi)+0.0000 SIN(Phi)+0.0000 COS(2*Phi)+0.0000 SIN(2*Phi)
fs= 1.4792+0.0841 COS(Phi)-3.0425 SIN(Phi)-1.5633 COS(2*Phi)+1.5213 SIN(2*Phi)

```
        Cr= 1.900
        Cs=  .100
        d=   .350 In.
        W=   .150 Lb/Ft
```

Sref(Ft)	Sstr(Ft)	X(Ft)	Y(Ft)	Z(Ft)	Phi(Deg)	Beta(Deg)	T(Lbs)
300.0	300.0	194.7	12.6	217.4	30.0	187.8	2300.5
350.0	350.0	238.9	16.0	240.4	25.5	189.0	2304.9
400.0	400.0	284.7	19.3	260.4	22.2	190.0	2309.8
450.0	450.0	331.4	22.6	277.9	19.5	191.1	2315.0
500.0	500.0	378.8	25.7	293.4	17.4	192.0	2320.5
523.0	523.0	400.8	27.2	300.0	16.6	192.4	2323.2

FINAL FORCE COMPONENTS
```
        Fx= -2226.63 Lb
        Fy=  -142.75 Lb
        Fz=  -647.27 Lb
```

Table 5. Physical characteristics of sample problem 2.

Speed, V (kn)	25.0
Water Density, ρ_w (lb-sec^2/ft^4)	1.9905
Air Density, ρ_a (lb-sec^2/ft^4)	0.0024
Towline	
Normal Drag Coefficient, C_r	0.15
Side Force Coefficient, C_s	0.0
Thickness, d (in.)	0.5
Weight in Water, W_w d(lb/ft)	0.2
Weight in Air, W_a (lb/ft)	0.55
Modulus of Elasticity, E (lb/in.^{2})	9.0×10^6
Structural Cross-Sectional Area, A_c (in.^{2})	0.1
Normal Loading Function, f_n	$-4.102 + 4.330 \cos\phi$ $+4.878 \sin\phi - 0.228 \cos2\phi$ $-2.165 \sin2\phi$
Tangential Loading Function, f_t	$0.078 + 0.383 \cos\phi$ $-0.078 \sin\phi$
Side Loading Function, f_s	$1.000 \sin\phi$
Athwartship Distance, Ystop (ft)	500.0
Tow Height, Zstop - Depth (ft)	15.0
Paravane	
Drag Force, F_x (lb)	-1000.0
Side Force, F_y (lb)	5000.0
Down Force, F_z (lb)	1000.0

Table 6. Program output for sample problem 2.

```
-------------------------------------------------------------------------------
SHIP TOWING A PARAVANE USING A FAIRED FIBERGLASS TOWLINE
-------------------------------------------------------------------------------

V=25.00 Knots

Rho=1.9905 Lb*Sec^2/Ft^4

fn=-4.1020+4.3300 COS(Phi)+4.8780 SIN(Phi)-0.2280 COS(2*Phi)-2.1650 SIN(2*Phi)
ft= 0.0780+0.3830 COS(Phi)-0.0790 SIN(Phi)+0.0000 COS(2*Phi)+0.0000 SIN(2*Phi)
fs= 0.0000+0.0000 COS(Phi)+1.0000 SIN(Phi)+0.0000 COS(2*Phi)+0.0000 SIN(2*Phi)

        Cr=   .150
        Cs= 0.000
        d=    .500 In.
        W=    .200 Lb/Ft
        E=   9.000 *10^6 Lb/In.^2
        Ac=   .100 In.^2

BODY FORCE COMPONENTS
        Fx= -1000.00 Lb
        Fy=  5000.00 Lb
        Fz=  1000.00 Lb
```

Sref(Ft)	Sstr(Ft)	X(Ft)	Y(Ft)	Z(Ft)	Phi(Deg)	Beta(Deg)	T(Lbs)
0.0	0.0	0.0	0.0	0.0	79.9	78.7	5196.2
50.0	50.3	12.0	-47.9	-9.6	73.6	78.6	5249.9
100.0	100.6	26.1	-94.6	-19.1	69.0	78.5	5322.3
150.0	150.9	47.8	-139.9	-28.4	65.0	78.4	5410.9
200.0	201.2	70.4	-183.9	-37.5	61.5	78.2	5513.2
250.0	251.5	95.6	-226.5	-46.4	58.5	78.1	5627.3
300.0	301.8	122.9	-267.9	-55.2	55.9	78.0	5751.2
350.0	352.1	151.9	-308.1	-63.8	53.6	77.9	5883.7
400.0	402.5	182.5	-347.2	-72.2	51.6	77.8	6023.4
450.0	452.8	214.3	-385.3	-80.5	49.9	77.7	6169.5
500.0	503.2	247.3	-422.4	-88.7	48.3	77.5	6321.1
515.5	518.8	257.7	-433.8	-91.2	47.9	77.5	6369.2

```
Rho=0.0024 Lb*Sec^2/Ft^4

fn=-4.1020+4.3300 COS(Phi)+4.8780 SIN(Phi)-0.2280 COS(2*Phi)-2.1650 SIN(2*Phi)
ft= 0.0780+0.3830 COS(Phi)-0.0780 SIN(Phi)+0.0000 COS(2*Phi)+0.0000 SIN(2*Phi)
fs= 0.0000+0.0000 COS(Phi)+1.0000 SIN(Phi)+0.0000 COS(2*Phi)+0.0000 SIN(2*Phi)

        Cr=   .150
        Cs= 0.000
        d=    .500 In.
        W=    .550 Lb/Ft
        E=   9.000 *10^6 Lb/In.^2
        Ac=   .100 In.^2
```

Sref(Ft)	Sstr(Ft)	X(Ft)	Y(Ft)	Z(Ft)	Phi(Deg)	Beta(Deg)	T(Lbs)
515.5	518.8	257.7	-433.8	-91.2	47.9	77.5	6369.2
550.0	553.5	281.0	-458.9	-96.9	47.9	77.3	6372.4
600.0	603.9	314.8	-495.3	-105.2	47.9	76.9	6377.1
606.4	610.3	319.1	-500.0	-106.2	47.9	76.9	6377.7

```
FINAL FORCE COMPONENTS
        Fx= -4274.22 Lb
        Fy=  4610.46 Lb
        Fz=  1072.54 Lb
```

Table 7. Physical characteristics of sample problem 3.

Speed, V (kn)	20.0
Water Density, ρ_w (lb-sec^2/ft^4)	1.9905
Air Density, ρ_a (lb-sec^2/ft^4)	0.0024
Towline (Pode Loading)	
Pode Frictional Parameter, f	0.007
Normal Drag Coefficient, C_r	1.80
Side Force Coefficient, C_s	0.0
Diameter, d (in.)	0.625
Weight in Water, W_w d(lb/ft)	0.000
Weight in Air, W_a (lb/ft)	0.130
Modulus of Elasticity, E (lb/in.^{2})	23,367.0 + 14.4 (T/A_c)
Cross-Sectional Area, A_c (in.^{2})	0.307
Distance Between Depressors, Smax1 (ft)	50.0
Depth to Lower Depressor, Zstop1 (ft)	75.0
Total Vertical Separation, Zstop2 (ft)	175.0
Paravane	
Drag Force, F_x (lb)	-300.0
Side Force, F_y (lb)	0.0
Down Force, F_z (lb)	1500.0

Table 8. Program output for sample problem 3.

```
--------------------------------------------------------------------------------
HELICOPTER TOWING TWO DEPRESSORS USING A BRAIDED NYLON TOWLINE
--------------------------------------------------------------------------------
```

V=20.00 Knots

Rho=1.9905 Lb*Sec^2/Ft^4

PODE LOADING

```
fn= 0.5000+0.0000 COS(Phi)+0.0000 SIN(Phi)-0.5000 COS(2*Phi)+0.0000 SIN(2*Phi)
ft= 0.0070+0.0000 COS(Phi)+0.0000 SIN(Phi)+0.0000 COS(2*Phi)+0.0000 SIN(2*Phi)
fs= 1.4792+0.0841 COS(Phi)-3.0425 SIN(Phi)-1.5633 COS(2*Phi)+1.5213 SIN(2*Phi)
```

```
        Cr= 1.800
        Cs= 0.000
        d=   .625 In.
        W=  0.000 Lb/Ft
        E=( 23.3670  +.0144*T/Ac ) *10^3 Lb/In.^2
        Ac=  .307 In.^2
```

BODY FORCE COMPONENTS
    Fx= -300.00 Lb
    Fy=   0.00 Lb
    Fz= 1500.00 Lb

Sref(Ft)	Sstr(Ft)	X(Ft)	Y(Ft)	Z(Ft)	Phi(Deg)	Beta(Deg)	T(Lbs)
0.0	0.0	0.0	0.0	0.0	78.7	0.0	1529.7
50.0	54.9	44.4	0.0	-28.1	14.7	0.0	1568.7

BODY FORCE COMPONENTS
    Fx= -300.00 Lb
    Fy=   0.00 Lb
    Fz= 1500.00 Lb

Sref(Ft)	Sstr(Ft)	X(Ft)	Y(Ft)	Z(Ft)	Phi(Deg)	Beta(Deg)	T(Lbs)
50.0	54.9	44.4	0.0	-28.1	46.2	0.0	2627.5
186.6	209.1	189.3	0.0	-75.0	8.4	0.0	2735.6

Rho=0.0024 Lb*Sec^2/Ft^4

PODE LOADING

```
fn= 0.5000+0.0000 COS(Phi)+0.0000 SIN(Phi)-0.5000 COS(2*Phi)+0.0000 SIN(2*Phi)
ft= 0.0070+0.0000 COS(Phi)+0.0000 SIN(Phi)+0.0000 COS(2*Phi)+0.0000 SIN(2*Phi)
fs= 1.4792+0.0341 COS(Phi)-3.0425 SIN(Phi)-1.5633 COS(2*Phi)+1.5213 SIN(2*Phi)
```

```
        Cr= 1.800
        Cs= 0.000
        d=   .625 In.
        W=   .130 Lb/Ft
        E=( 23.3670  +.0144*T/Ac ) *10^3 Lb/In.^2
        Ac=  .307 In.^2
```

Sref(Ft)	Sstr(Ft)	X(Ft)	Y(Ft)	Z(Ft)	Phi(Deg)	Beta(Deg)	T(Lbs)
186.6	209.1	189.3	0.0	-75.0	8.4	0.0	2735.6
746.9	842.2	814.4	0.0	-175.0	9.8	0.0	2747.6

FINAL FORCE COMPONENTS
    Fx= -2707.38 Lb
    Fy=   0.00 Lb
    Fz=   469.51 Lb

ACKNOWLEDGMENTS

APPENDIX

HP-9836 PROGRAM LISTING

```
10 |------------------------------------------------------R. KNUTSON-----11/13/85-----
20 |
30 |                              Program CABL36 calculates the three-dimensional
40 | CABL36                       static configuration of an extensible, flexible
50 |                              cable in a uniform stream.
60 |
70 |--------------------------------------------------------------------------------
80 |
90 |                              Main input section
100|
110|--------------------------------------------------------------------------------
120       RAD
130       DIM A$[80]
140 M1:   Output=0
150       Continue=0
160       S=0
170       Ss=0
180       X=0
190       Y=0
200       Z=0
210       T=0
220       Fx=0
230       Fy=0
240       Fz=0
250       INPUT "FOR HARDCOPY, ENTER: 1 [For CRT, press CONT]",Output
260       IF Output=0 THEN PRINTER IS 1
270       IF Output=1 THEN PRINTER IS 701
280       INPUT "ENTER: TITLE",A$
290       PRINT "-----------------------------------------------------------------
------------------"
300       PRINT A$
310       PRINT "-----------------------------------------------------------------
------------------"
320       PRINT
330       INPUT "ENTER SPEED: V (Knots)",V
340       PRINT USING I1;"V=",V,"Knots"
350 I1:   IMAGE 2A,DD.2D,X,5A
360 M2:   PRINT
370       INPUT "ENTER FLUID MASS DENSITY: Rho (Lb*Sec^2/Ft^4)",Rho
380       PRINT USING I2;"Rho=",Rho,"Lb*Sec^2/Ft^4"
390 I2:   IMAGE 4A,Z.4D,X,13A
400       INPUT "ENTER CABLE LOADING: Pode=1; Ribbon=2; Other=3",Loading
410        IF Loading=1 THEN GOSUB Pode
420        IF Loading=2 THEN GOSUB Ribbon
430        IF Loading=3 THEN GOSUB Other_loading
440       PRINT
450       PRINT USING I3;"fn=",Fa0,Fa1,"COS(Phi)",Fb1,"SIN(Phi)",Fa2,"COS(2*Phi)"
,Fb2,"SIN(2*Phi)"
460       PRINT USING I3;"ft=",Ga0,Ga1,"COS(Phi)",Gb1,"SIN(Phi)",Ga2,"COS(2*Phi)"
,Gb2,"SIN(2*Phi)"
470       PRINT USING I3;"fs=",Ha0,Ha1,"COS(Phi)",Hb1,"SIN(Phi)",Ha2,"COS(2*Phi)"
,Hb2,"SIN(2*Phi)"
480 I3:   IMAGE 3A,MZ.4D,2(SZ.4D,X,8A),2(SZ.4D,X,10A)
490       PRINT
500       INPUT "ENTER CABLE NORMAL DRAG COEFF: Cr",Cr
510       PRINT USING I4;"Cr=",Cr
520 I4:   IMAGE 4X,3A,DD.3D
530       INPUT "ENTER CABLE SIDE FORCE COEFF: Cs",Cs
540       PRINT USING I5;"Cs=",Cs
550 I5:   IMAGE 4X,3A,MD.3D
```

```
560        INPUT "ENTER CABLE THICKNESS: d (In.)",Dia
570        PRINT USING I6;"d=",Dia,"In."
580 I6:    IMAGE 4X,2A,3D.3D,X,3A
590        INPUT "ENTER CABLE WEIGHT IN FLUID: W (Lb/Ft)",W
600        PRINT USING I7;"W=",W,"Lb/Ft"
610 I7:    IMAGE 4X,2A,MDD.3D,X,5A
620        INPUT "ENTER CABLE ELASTICITY: Non-Elastic=1; Elastic=2",Elas
630        IF Elas<>2 THEN M3
640        INPUT "ENTER MODULUS OF ELAS: E=E0+E1*T/Ac (Lb/In.^2)",E0,E1
650        IF E1=0 THEN PRINT USING I8;"E=",E0/1000000,"*10^6 Lb/In.^2"
660 I8:    IMAGE 4X,2A,3D.3D,X,14A
670        IF E1<>0 THEN PRINT USING I9;"E=(",E0/1000,E1/1000,"*T/Ac) *10^3 Lb/In
.^2"
680 I9:    IMAGE 4X,3A,3D.4D,SDD.4D,21A
690        INPUT "ENTER CABLE CROSS-SECTIONAL AREA: Ac (In.^2)",Ac
700        PRINT USING I10;"Ac=",Ac,"In.^2"
710 I10:   IMAGE 4X,3A,DD.3D,X,5A
720 M3:    IF Continue=2 THEN M5
730 M4:    INPUT "ENTER BODY FORCE COMPONENTS: Fx,Fy,Fz (Lb)",Fxo,Fyo,Fzo
740        PRINT
750        PRINT "BODY FORCE COMPONENTS"
760        PRINT USING I11;"Fx=",Fxo,"Lb"
770        PRINT USING I11;"Fy=",Fyo,"Lb"
780        PRINT USING I11;"Fz=",Fzo,"Lb"
790 I11:   IMAGE 4X,3A,MSD.2D,X,2A
800 M5:    INPUT "ENTER MAXIMUM CABLE LENGTH: Smax (Ft)",Smax
810        INPUT "ENTER CABLE LENGTH PRINTOUT INTERVAL: Sinc (Ft)",Sinc
820        Cstop=0
830        Xstop=10^5
840        Ystop=10^5
850        Zstop=10^5
860        Phidstop=-10^3
870        INPUT "ENTER LIMIT: Xstop (Ft) [If none, press CONT]",Xstop
880        INPUT "ENTER LIMIT: Ystop (Ft) [If none, press CONT]",Ystop
890        INPUT "ENTER LIMIT: Zstop (Ft) [If none, press CONT]",Zstop
900        INPUT "ENTER LIMIT: Phistop (Deg) [If none, press CONT]",Phidstop
910        Phistop=Phidstop/57.2958
920        PRINT
930        PRINT " Sref(Ft) Sstr(Ft)   X(Ft)    Y(Ft)    Z(Ft)   Phi(Deg) Beta(De
g)    T(Lbs)"
940        IF Continue<2 THEN GOSUB Tangle
950        GOSUB Integrator
960        Continue=0
970        INPUT "ADD BODY, ENTER: 1; ADD CABLE, ENTER: 2 [NEW CASE, press CONT]",
Continue
980        IF Continue=1 THEN M4
990        IF Continue=2 THEN M2
1000       PRINT
1010       PRINT "FINAL FORCE COMPONENTS"
1020       PRINT USING I11;"Fx=",Fx,"Lb"
1030       PRINT USING I11;"Fy=",Fy,"Lb"
1040       PRINT USING I11;"Fz=",Fz,"Lb"
1050       IF Output=1 THEN PRINT CHR$(12)
1060       GOTO M1
```

37

```
1070 !------------------------------------------------------------------
1080 !
1090 Tangle: !                        Subroutine "Tangle" calculates starting cable
1100 !                                angles and tension from input force components.
1110 !
1120 !------------------------------------------------------------------
1130     Fx=Fx+Fxo
1140     Fy=Fy+Fyo
1150     Fz=Fz+Fzo
1160     Tzy=SQR(Fz*Fz+Fy*Fy)
1170     T=SQR(Tzy*Tzy+Fx*Fx)
1180      IF Tzy=0 THEN Beta=0
1190      IF (Fz=0) AND (Fy<>0) THEN Beta=PI*Fy/(2*ABS(Fy))
1200      IF Fz>0 THEN Beta=ATN(Fy/Fz)
1210      IF (Fz<0) AND (Fy=0) THEN Beta=PI
1220      IF (Fz<0) AND (Fy<>0) THEN Beta=ATN(Fy/Fz)+PI*Fy/ABS(Fy)
1230      IF (Fx=0) AND (Tzy<>0) THEN Phi=PI/2
1240      IF Fx<0 THEN Phi=ATN(-Tzy/Fx)
1250      IF Fx>0 THEN Phi=ATN(-Tzy/Fx)+PI
1260      IF T=0 THEN GOSUB Critang
1270      IF T<.1 THEN T=.1
1280     RETURN
1290 !------------------------------------------------------------------
1300 !
1310 !                                Subroutine "Critang" calculates critical angles
1320 Critang: !                       to begin the integration when the starting
1330 !                                tension is zero.
1340 !
1350 !------------------------------------------------------------------
1360     Beta=0
1370     Phi=0
1380      IF W=0 THEN P3
1390     R=.118723*Rho*Cr*Dia*V*V
1400     Fs=.118723*Rho*Cs*Dia*V*V
1410     Phinc=.09
1420 P1: Sp=SIN(Phi)
1430     Cp=COS(Phi)
1440     S2p=SIN(2*Phi)
1450     C2p=COS(2*Phi)
1460     H=Fs*(Ha0+Ha1*Cp+Hb1*Sp+Ha2*C2p+Hb2*S2p)
1470      IF ABS(W)>=ABS(H) THEN P2
1480     Phinc=Phinc/2
1490     Phi=Phi-Phinc
1500     GOTO P1
1510 P2:  IF W>0 THEN Beta=ASN(H/W)
1520      IF (W<0) AND (H>=0) THEN Beta=-ASN(H/W)-PI
1530      IF (W<0) AND (H<0) THEN Beta=-ASN(H/W)+PI
1540     F=-R*(Fa0+  ...p+rb1*...  2*C2p+Fb2*S2p)
1550     Sum=F+W*COS(Phi)*COS(Beta)
1560      IF ABS(Sum)<.00001 THEN P3
1570      IF Sum<0 THEN Phinc=Phinc/2
1580     Phi=Phi+Phinc*Sum/ABS(Sum)
1590     GOTO P1
1600 P3:RETURN
```

38

```
1610 !---------------------------------------------------------------------------
1620 !
1630 !                                 Subroutine "Integrator" solves the differential
1640 Integrator: !                     equations of cable force equilibrium using a
1650 !                                 self-starting, modified Euler's method.
1660 !
1670 !---------------------------------------------------------------------------
1680     Sinc=ABS(Sinc)
1690      IF Smax<0 THEN Sinc=-Sinc
1700     Dias=Dia
1710     Ws=W
1720 N1: Phid=Phi*57.2958
1730     Betad=Beta*57.2958
1740     PRINT USING I12;S,Ss,X,Y,Z,Phid,Betad,T
1750 I12:IMAGE S(M5D.D,X),2X,2(M3D.D,4X),7D.D
1760      IF (Cstop=1) OR (ABS(Smax-S)<=.01) THEN N9
1770     S1=INT((ABS(S)+.01)/ABS(Sinc))*Sinc+Sinc
1780 N2: Dels=S1-S
1790      IF ABS(Dels)>50 THEN Dels=50*Dels/ABS(Dels)
1800      IF ABS(S+Dels)>=ABS(Smax) THEN Dels=Smax-S
1810 N3: Delss=Dels
1820     I=0
1830     Delp=0
1840     Delb=0
1850     Delt=0
1860 N4: I=I+1
1870     Delp1=Delp
1880     Delb1=Delb
1890     Betav=Beta+Delb/2
1900     Phiav=Phi+Delp/2
1910     Tav=T+Delt/2
1920      IF Elas<>2 THEN N5
1930     E=E0+E1*Tav/Ac
1940      IF E1=0 THEN B=1+Tav/(Ac*E)
1950      IF E1<>0 THEN B=1+LOG(E/E0)/E1
1960     Dias=Dia*SQR(1/B)
1970     Ws=W*(1/B)
1980     Delss=Dels*B
1990 N5: R=.118723*Rho*Cr*Dias*V*V
2000     Fs=.118723*Rho*Cs*Dias*V*V
2010     Sp=SIN(Phiav)
2020      IF ABS(Sp)<.0001 THEN Sp=.0001
2030     Cp=COS(Phiav)
2040     S2p=SIN(2*Phiav)
2050     Sb=SIN(Betav)
2060     Cb=COS(Betav)
2070     Phiav1=ABS(ASN(SIN(Phiav)))
2080     Sp1=SIN(Phiav1)
2090     Cp1=COS(Phiav1)
2100     S2p1=SIN(2*Phiav1)
2110     C2p1=COS(2*Phiav1)
2120     F1=-R*(Fa0+Fa1*Cp1+Fb1*Sp1+Fa2*C2p1+Fb2*S2p1)
2130     G1=-R*(Ga0+Ga1*Cp1+Gb1*Sp1+Ga2*C2p1+Gb2*S2p1)
2140     H1=Fs*(Ha0+Ha1*Cp1+Hb1*Sp1+Ha2*C2p1+Hb2*S2p1)
2150      IF Sp>=0 THEN F=F1
2160      IF Sp<0 THEN F=-F1
2170      IF Cp>=0 THEN G=G1
2180      IF Cp<0 THEN G=-G1
2190      IF (Loading<=2) AND (S2p>=0) THEN H=H1
2200      IF (Loading<=2) AND (S2p<0) THEN H=-H1
```

```
2210      IF (Loading>2) AND (Sp>=0) THEN H=H1
2220      IF (Loading>2) AND (Sp<0) THEN H=-H1
2230    Delt=(-6+Ws*Sp*Cb)*Delss
2240    Delb=(H-Ws*Sb)*Delss/(Tav*Sp)
2250    Delp=(F+Ws*Cp*Cb)*Delss/Tav
2260    Dels1=Dels
2270      IF I>10 THEN Dels=Dels1/2
2280      IF ABS(Delb)>.09 THEN Dels=ABS(.07/Delb)*Dels1
2290      IF ABS(Delp)>.09 THEN Dels=ABS(.07/Delp)*Dels1
2300      IF Dels<>Dels1 THEN N3
2310      IF (ABS(Delp-Delp1)>.0002) OR (ABS(Delb-Delb1)>.0002) THEN N4
2320    S=S+Dels
2330    Ss=Ss+Delss
2340    X=X+Delss*Cp
2350    Y=Y-Delss*Sp*Sb
2360    Z=Z-Delss*Sp*Cb
2370    T=T+Delt
2380    Phi=Phi+Delp
2390    Beta=Beta+Delb
2400  *   IF Cstop=1 THEN N7
2410      IF ABS(X)>ABS(Xstop) THEN N6
2420      IF ABS(Y)>ABS(Ystop) THEN N6
2430      IF ABS(Z)>ABS(Zstop) THEN N6
2440      IF Phi<Phistop THEN N6
2450      IF (ABS(Smax-S)>.01) AND (ABS(S1-S)>.01) THEN N2
2460    GOTO N1
2470 N6: Cstop=1
2480 N7:  IF ABS(ABS(X)-ABS(Xstop))<.01 THEN N1
2490      IF ABS(ABS(Y)-ABS(Ystop))<.01 THEN N1
2500      IF ABS(ABS(Z)-ABS(Zstop))<.01 THEN N1
2510      IF ABS(Phi-Phistop)<.0005 THEN N1
2520    Dels=ABS(Dels)
2530      IF ABS(X)>ABS(Xstop) THEN N8
2540      IF ABS(Y)>ABS(Ystop) THEN N8
2550      IF ABS(Z)>ABS(Zstop) THEN N8
2560      IF Phi<Phistop THEN N8
2570    Dels=Dels/2
2580      IF S<0 THEN Dels=-Dels
2590    GOTO N3
2600 N8: Dels=-Dels/2
2610      IF S<0 THEN Dels=-Dels
2620    GOTO N3
2630 N9: Fx=-T*COS(Phi)
2640    Fy=T*SIN(Phi)*SIN(Beta)
2650    Fz=T*SIN(Phi)*COS(Beta)
2660    RETURN
```

40

```
2670 !------------------------------------------------------------------------
2680 !
2690 Pode: !                          Subroutine "Pode" provides coefficients for
2700 !                                Pode or bare cable loading functions.
2710 !
2720 !------------------------------------------------------------------------
2730     Fa0=.5
2740     Fa1=0
2750     Fb1=0
2760     Fa2=-.5
2770     Fb2=0
2780     Ga1=0
2790     Gb1=0
2800     Ga2=0
2810     Gb2=0
2820     Ha0=1.4792
2830     Ha1=.0841
2840     Hb1=-3.0425
2850     Ha2=-1.5633
2860     Hb2=1.5213
2870     PRINT
2880     PRINT "PODE LOADING"
2890     INPUT "ENTER PODE FRICTIONAL PARAMETER: f",6a0
2900     RETURN
2910 !------------------------------------------------------------------------
2920 !
2930 Ribbon: !                        Subroutine "Ribbon" provides coefficients for
2940 !                                ribbon-faired cable loading functions.
2950 !
2960 !------------------------------------------------------------------------
2970     Fa0=.4986
2980     Fa1=-.2499
2990     Fb1=.2527
3000     Fa2=-.2487
3010     Fb2=0
3020     Ga0=-.2255
3030     Ga1=.3417
3040     Gb1=.2255
3050     Ga2=0
3060     Gb2=-.0811
3070     Ha0=1.4792
3080     Ha1=.0841
3090     Hb1=-3.0425
3100     Ha2=-1.5633
3110     Hb2=1.5213
3120     PRINT
3130     PRINT "RIBBON LOADING"
3140     RETURN
3150 !------------------------------------------------------------------------
3160 !
3170 Other_loading: !                 Subroutine "Other_loading" allows input of
3180 !                                generalized cable loading functions.
3190 !
3200 !------------------------------------------------------------------------
3210     INPUT "ENTER NORMAL LOADING FUNC, fn: A0,A1,B1,A2,B2",Fa0,Fa1,Fb1,Fa2,F
b2
3220     INPUT "ENTER TANGENTIAL LOADING FUNC, ft: A0,A1,B1,A2,B2",Ga0,Ga1,Gb1,G
a2,Gb2
3230     INPUT "ENTER SIDE LOADING FUNC, fs: A0,A1,B1,A2,B2",Ha0,Ha1,Hb1,Ha2,Hb2
3240     RETURN
3250 END
```

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